BIOGRAPHY

Jerry P. Eaton has done geophysical research with the U.S. Geological Survey since being awarded the Ph.D. in Geophysics from the University of California, Berkeley, in 1953. Until 1961, he was associated with the Geological Survey's Hawaiian Volcano Observatory, first as Geophysicist and later as Scientist-in-Charge. At the Observatory, he organized and conducted research in seismology and general geophysics on Hawaiian volcanoes and correlated the results of those studies with geophysical and geochemical investigations of the volcanoes. In 1961, he joined the Geological Survey Crustal Studies Branch, where he developed an earthquake seismology program in the Rocky Mountain-Great Plains region, and participated in the analysis of data from explosion-seismology crustal-refraction studies of crustal and upper-mantle structure in the western United States. He joined the staff of the National Center for Earthquake Research (NCER) at its formation in 1965, and has played a major role in shaping of facets of the NCER Program. Dr. Eaton is Past President (1966-67) and Member of the Board of Directors (1961-1970) of the Seismological Society of America, and is currently Acting Chief of the Office of Earthquake Research and Crustal Studies, U.S. Geological Survey.

Wayne H. Jackson received a degree in Geophysical Engineering from the Colorado School of Mines in 1951. Following a year of work as Physicist with the U.S. Navy Electronic Laboratory, he joined the U.S. Geological Survey, where he served as Geophysicist, first on gravity, seismic, and magnetic projects in the Colorado Plateau area, and later in Cuba. From 1956 to 1965, Mr. Jackson worked on laboratory and field studies using seismic and gravity methods in the western United States. He has been in charge of all seismic operations of the National Center for Earthquake Research Program (NCER) since it was established in 1965. Mr. Jackson is author or co-author of more than 40 papers and reports on geophysical subject.

SATELLITE RELAY TELEMETRY OF SEISMIC DATA IN EARTHQUAKE PREDICTION AND CONTROL

Wayne H. Jackson and Jerry P. Eaton

INTRODUCTION

The Satellite Telemetry Earthquake Monitoring Program was started in FY 1968 to evaluate the applicability of satellite relay telemetry in the collection of seismic data from a large number of dense seismograph clusters laid out along the major fault systems of western North America. Prototype clusters utilizing phone-line telemetry were then being installed by the National Center for Earthquake Research (NCER) in 3 regions along the San Andreas fault in central California; and the experience of installing and operating the clusters and in reducing and analyzing the seismic data from them was to provide the raw materials for evaluation in the satellite relay telemetry project.

Initially, it was assumed that the satellite relay would provide a large number of continuous voice-grade communications channels that would link clusters to a central data recording and processing facility. The principal advantages of the satellite relay system over commercial telephone or microwave systems were: (1) it could be made less prone to massive failure during a major earthquake; (2) it could be extended readily into undeveloped regions; and (3) it could provide flexible, uniform communications over large sections of major global tectonic zones.

Fundamental characteristics of a communications system to cope with the large volume of raw data collected by a short-period seismograph network are discussed.

Aside from the relay system itself, which was outside the scope of this study, the most urgent need was for the development of a flexible, reliable, inexpensive means of gathering data from individual sensors in a cluster into a central point from which the satellite relay would be reached. Accordingly, during FY 1968, emphasis was placed on the investigation of available or promising systems for collecting seismic-cluster data at a central point in a format which would be convenient for long-range telemetry via relay satellite or phone line. To stimulate development of a low-power radio data link, a development contract was issued (to DEVELCO, Mountain View) for the construction of a 0.1-watt FM VHF transmitter.

Near the end of FY 1968, we learned that the first satellites (ERTS) that might become available for testing a seismic-data-relay system would provide only for periodic relay of a very small amount of data. These restrictions forced a fundamental reevaluation of the experiment that was being formulated. Our best information on the cost and complexity of the electronic equipment required to transmit data to the satellite indicated that a number of such platforms should be kept to a minimum. Thus, a high priority was maintained on the development of a reliable inexpensive communications link to transmit data from a number of sensors to a central platform.

U.S. Geological Survey, Department of the Interior

The project was extended into FY 1969, with some additional support, to study possible applications of the ERTS system to earthquake prediction and related geophysical problems. Work was continued on several topics:

1. 7 VHF radio data-transmission links were purchased. They were tested and evaluated under a variety of field conditions in California, Nevada, Colorado, and Hawaii and were found to operate reliably over line-of-sight paths more than 50 km long with only 0.1-watt of radiated power. A summary of the work on the development and testing of the low-power radio links is presented.

2. Various sources of power for the low-power seismic units and radio data links were investigated. The simplest inexpensive, large capacity power source discovered is the air cell, a primary cell utilizing oxygen from the air as a depolarizing agent. These cells were tested extensively under field conditions of extreme heat and cold. The principal results of investigations of power supplies are summarized.

3. A number of slowly varying non-seismic geophysical parameters that might contribute to a better understanding of earthquakes were studied from the viewpoint of the instrumentation required to measure them and the volume of data required to specify them. Tilt, strain, and fault-creep measurements, which are important because they characterize kinematic changes in the earthquake-producing system, were the subjects of chief concern.

As a result of the studies carried out in FY 1968 and FY 1969, a shift in emphasis in the satellite-relay telemetry of seismic data experiment was proposed. Pending the perfection of methods and equipment for the in-the-field automatic processing of seismic network data, nothing short of a continuously-available synchronous satellite will suffice for telemetry of raw data from even a moderate size microearthquake network. On the other hand, the polar-orbit ERTS system will fulfill the data collection requirements of global volcano surveillance networks based on condensed-data seismic and tiltmeter systems installed on the individual volcanoes under study.

The problems and requirements of a worldwide volcano surveillance system are briefly discussed, along with descriptions of the new instrumentation that will be needed for such a network and of preliminary field studies that will be required to test these instruments. Sixteen preliminary platform locations in Hawaii, Continental United States, and Central America are suggested for initial tests.

SEISMOGRAPH DATA TRANSMISSION

A. Basic Methods

Real-time transmission of seismic data from a number of remote stations to a data-collection center is generally accomplished by radio, commercial telephone line, or a combination of these two. The usable band of frequencies available with the transmission link is in the range of 300 to 3000 Hz, a bandwidth of about 2700 Hz. The desired range of short-period seismic signals is generally from 0.1 to 25 or 30 Hz, which lies below the band of frequencies that can be handled directly by the communciations link. Remote seismograph stations are generally arranged in "clusters" so even if direct transmission of seismic data were possible over radio and telephone links, a separate link for each station would be impracticable.

There are two basic methods of transmitting more than one data signal over a communications link: frequency-division multiplexing and time-division multiplexing. With frequency-division multiplexing, all channels occupy the entire frequency band, but each channel is connected to the transmission medium for a short time. Each has advantages and disadvantages.

B. Frequency-Division Multiplexing

Frequency-division multiplexing (FDM) is the oldest and most widely used method. FDM equipment has been made extremely reliable throughout its many years of use. The telephone company's carrier equipment, a type of FDM, has been in use for many tens of years. In using FDM for transmitting seismograph data, the signal from a seismometer (figure 1)is amplified and used to frequency-modulate a subcarrier frequency which is compatible with the transmission link. The frequency is generated by an oscillator, commonly called a voltage controlled oscillator (VCO) because the output frequency is controlled by the amplitude of the input signal. The electronic circuit of the VCO is arranged so that an upward ground motion (positive output voltage from a vertical seismometer) results in an increased VCO frequency, or a positive deviation from center frequency; while a downward ground motion results in a decreased VCO frequency or a negative deviation. With a zero input signal, the VCO oscillates at its center frequency.

An important consideration in the design of a seismograph data transmission system is in the bandwidth of the data channel. Since all data channels are expected to carry similar signals (0.1 to 25 Hz), a constant-bandwidth system is indicated, or each channel will occupy the same bandwidth. It is common practice to design a VCO so that the peak deviation from center frequency is 5 times the data frequency, or its deviation ratio is 5. Lower deviation radios are used to reduce data channel bandwidth but at the expense of data accuracy, harmonic distortion and signal-to-noise improvement. Another important consideration is in channel spacing. Guardbands, or the unused spacing between channels should be as wide as possible to prevent "crosstalk" between adjacent channels.

The seismic data transmission system now in use at NCER utilizes a total of 7 data channels of 250 Hz each, separated by guardbands of 90 Hz. An 8th channel, of center frequency 3060 Hz, has been added when the telephone lines pass frequencies as high as 3185 Hz.

C. Time-Division Multiplexing

Time-division multiplexing (TDM) is becoming more prevalent as the costs of digital equipment is being reduced, as computer data processing and analysis is required, and as high speed and greater precision is needed. Various types of pulse modulation are in use, but pulse-code modulation (PCM) appears to be the most useful in the transmission of large amounts of earthquake data. With PCM, each data channel is sampled in a regular sequence, and the signals are converted into a series of digits or characters. The samples from the various channels are interleaved in time to form a single-pulse train.

The primary advantage of PCM is its ability to be adapted for direct use with digital data-processing equipment and computers. It has an unlimited dynamic range and exceptionally good data accuracy. The Large Aperture Seismic Array (LASA) in Montana uses digital transmission even over the relatively short distances involved. The analog signal from each station of a subcluster is transmitted by buried cable to the Data Center at Billings. The LASA raw data has a dynamic range of over 72 db. Good FDM, or analog, data transmission may expect no greater than 60 db dynamic range.

An important disadvantage of PCM transmission is its bandwidth extravagance. If frequencies below 3000 cycles per second are to be transmitted by PCM, a theoretical minimum of 6000 samples per second are needed. Assuming a 7-bit sample (42 db dynamic range) is required, a total of 42,000 bits per second will be transmitted. To transmit this bit rate, a bandwidth of 21 kilohertz is necessary.

D. Comparing FDM and TDM

There is no simple way to compare analog, or FM transmission, with digital, or PCM transmission, because of the large variation in data to be transmitted. These methods, however, can be contrasted in general terms.

Costs of terminal equipment are important. Little, if any of the circuitry is common to the separate FM channels. Frequency-division multiplexing costs are essentially proportional to the number of channels transmitted over one transmission link. With time-division multiplexing, much of the circuitry is common so this type of transmission is more economical for large numbers of channels. A few channels of high frequency data could absorb the entire capacity of a PCM system. PCM transmission is very well suited for handling large numbers of low-speed data channels.

One of the most important points of comparison is the dynamic range of the system. Over an optimum transmission path a maximum of 60 db may be expected from FM equipment. If a better dynamic range is required, a PCM system will be necessary. PCM transmissions are superior to FM transmissions over noisy communications links.

An extremely important advantage of the FM over the PCM system is the manner of combining, or multiplexing, data channels for transmission over a communications link. The multiplexing of FM channels is simply a summation, or mixing process, that can be accomplished at any point along the transmission path. This is very useful in transmitting earthquake data by radio to a collecting point. Each radio relay station can also be a seismograph station and/or a subcollecting point. Additional data channels can be inserted into the transmitted "stream" of data with little or no additional equipment. The addition of channels in a TDM system cannot be done as easily because of the difficulties in synchronizing the additional channel data bits with the available time gaps in the data "stream." There are many ways of solving this problem, but usually at the expense of flexibility, additional equipment, and channel capacity. Multiplexing in a TDM system is best accomplished at a central point, such as is done at the LASA subarray vaults.

The proper system to be used in the collection of earthquake data will depend upon the cost, noise characteristics, available bandwidth, etc., of the transmission path. It is most likely that, for remote sensing, the data will be collected locally for processing using a frequency division system, then the processed data would be retransmitted via satellite by a time-division system. This would maintain flexibility and yet require a relatively uncomplicated electronic system.

RADIO TRANSMISSION LINKS

A. Practical Considerations

For the radio transmission link to be useful in collecting and transmitting earthquake data, it is essential that the remote equipment, including power supplies, be portable; reliable; require as little power as possible; be able to run for 12 to 18 months before changing batteries; and provide continuous 24-hr per day duty over wide ranges of temperature and humidity. Under most circumstances, it should be possible to arrange instrument locations so that line-of-sight transmission will be possible. Although eventually the collected data will be processed at one point for retransmission to an orbiting or stationary satellite, for purposes of evaluating data, it would be useful if each radio link have similar bandpass characteristics as telephone voice-grade lines. This would make it possible to have data collected either by a radio link, a telephone line, or both, for transmission to a data collection center. Voice-grade telephone lines pass, in general, frequencies in the range 300 to 3000 Hz.

B. Transmitter Modulation and Frequency

For continuous line-of-sight transmission, frequency modulation in the range above 100 MHz is less affected by atmospheric noise than amplitude-modulated radio at lower frequencies. Therefore, FM is preferable to AM. Of the frequencies in the VHF (30 to 300 MHz), UHF (300 to 3000 MHz), and the microwave frequencies (above 3000 MHz), the VHF frequencies were preferred because of the availability of suitable equipment. UHF and microwave radio equipment were available but at considerably higher cost per radio link. Although radio frequency assignments in this band are becoming extremely scarce, 9 splinter channel frequencies (167 to 170 MHz) became available on a non-interference basis. Even though the radio propagation path is not precisely an optical straight-line path at these frequencies, the same frequencies can be used over and over again in many sites provided they are not in optical sight of one another

C. Transmitter Power

An extremely important consideration in the design of the telemetry system is the power required by the radio transmitter to provide reliable transmission over the maximum distance to be expected. Power requirements for the entire remote system must be kept to a minimum; over half of the weight is expected to be that of the batteries; and a large part of the maintenance costs are expected to be in replacing batteries over regular periods.

There is, however, a practical limitation on the minimum radio-frequency power supplied to the antenna. In the RF power range (5 watts and less) required for this work, the efficiency of power output to power input increases with increased RF output power. This is due in part to the constant power drain of the early stages of the transmitter that do not contribute to the output power.

Assuming a transmitter output power of 100 milliwatts is the minimum practical power, its performance may be calculated using the range equation:

Let P_{rad} = radiated power, watts

P_{rec} = received power, watts

r = distance, transmitter to receiver, meters

G_T = transmitter antenna gain

A_R = receiver antenna capture area

G_R = receiver antenna gain

The power at the receiver is given by

$$P_{rec} = \frac{P_{rad} G_T A_R}{4\pi r^2}$$

The signal-to-noise ratio at the receiver is given by

$$S/N = \frac{P_{rec}}{P_{SEN}}$$ where P_{SEN} is receiver threshold sensitivity

For example:

P_{rad} = 100 mw

r = 10 km

G_T = 6 (7.8 db)

$$A_r = \frac{2G_r}{4\pi} = \frac{(c/f)^2 G_r}{4\pi} = \frac{\left[\frac{(3 \times 10^8)}{(1.7 \times 10^8)}\right] \times 6}{4\pi} = 1.49\ m^2$$

$P_{SEN} = 0.5 \times 10^{-16}$

Then

$$P_{rec} = \frac{(10^{-1})(6)(1.49)}{(4\pi)(10^4)^2} = 0.71 \times 10^{-9}\ w$$

$$S/N = \frac{0.71 \times 10^{-9}}{0.5 \times 10^{-16}} = 1.42 \times 10^7 = +71.1\ db$$

For 100 km, S/N = 71.1-20 = 51.1 db

For 10 km, S/N = 71.1 db

The calculations suggest that for line-of-sight transmission, under ideal circumstances, a 100-milliwatt transmitter could be used to send data over distances as great as 100 km.

A DEVELCO, Model 3401, VHF 100-milliwatt transmitter was delivered in June 1968. Preliminary tests indicated that the performance of the radio link did not deviate greatly from the calculated performance for line-of-sight travel paths, but the signal-to-noise ratios of 6 db and less were measured for grazing paths through industrial areas, high-power lines, etc.

In July 1968, a seismograph station was installed on Poverty Ridge in the Diablo Range about 45 km southeast of Menlo Park using the prototype radio transmission link. Through the 1-yr. period, July 1968 to July 1969, seismograph data of excellent quality was recorded.

Since this time radio links have been utilized by a number of projects throughout the country to transmit seismic data from remote locations to telephone terminals. Presently a total of 24 VHF radio links are in use at locations in California, Nevada, Colorado, and Hawaii.

The advancement in the state-of-the-art has made a second generation of radios possible. Motorola Communications has delivered radio transmitters and receivers requiring considerably lower input power than the first generation.

POWER SUPPLIES

The utilization of an efficient system to power the remote sensors and associated equipment is extremely critical. A large part of the weight of the remote station, and a large part of the attention necessary for operation of the station, can be attributed to the power supply. The seismograph station, because it is continuously operated, requires the highest power drain of all the fault-zone instruments. Studies of available power supplies have therefore been based upon the requirements of a remote station consisting of a seismic preamplifier-subcarrier oscillator and a 100-milliwatt VHF transmitter.

When properly installed, a seismograph station has a yearly survival probability of about 95%. Proper installation includes avoiding areas susceptible to flooding, care taken to minimize pilferage, etc. Failure has been due, in large part, to lightning strikes in the vicinity of a station or telephone line. Lightning arrestors utilized in interfacing the equipment to telephone lines and to radio transmitters may have reduced the failure rate, but we have not been able to devise a reliable method to measure potentially damaging voltage transients in a given area. When possible, radio transmitters are not placed on peaks, ridges, or other locations which may receive lightning strikes.

Assuming a power supply will be required for a minimum of one year, various types of sources were investigated. Power drain for the remote seismograph station (table 1) indicates that about 7000 watt-hours will be required to operate the VCO preamplifier and the VHF transmitter for one year, and 12,600 watt-hours per year for a relay station.

Various types of power sources were studied (table 2) to determine the cost, weight, life, and other factors having a bearing on suitability to power remote stations. Lead-acid batteries are immediately rejected because of their short shelf-life. The most promising battery tested to date for powering remote stations is made up of Union Carbide "air cells," primary, or non-rechargeable, cells. Each cell is made up of zinc-carbon electrodes with potassium hydroxide electrolite. These batteries have been in use for many years in powering railway signals and in maritime lighting. Carnegie Institute, Washington, D. C., used "air cells" to power seismograph stations in South America several years ago. The high-power density, low-cost per watt-hour, and long shelf-life features are particularly important in considering power supplies for remote locations. The batteries are rated at operating temperatures down to 0° F. One possible disadvantage offered by these batteries is in the necessity of supplying air as required in the depolarizing process. In cold regions (temperature below 0° F), all equipment will have to be buried beneath the ground surface; a "snorkel" will be required to supply air.

Isotope generators may be useful in remote areas to power a permanent station, but the extremely high purchase cost (about $9000 at this time) must be weighed against transportation and maintenance costs of less expensive power supplies.

Although solar cell charging systems are relatively expensive, the power yield per pound is extremely high. Use of this type of power supply is especially advantageous for stations located in areas serviced by small aircraft or in locations where equipment and batteries have to be packed in, or for other reasons where weight may be a problem. The primary disadvantage of this power supply is the cost, which for an average station may be on the order of $1000.

In areas where propane or butane gas is available, thermoelectric generators are probably the most economical type of power supply for unattended stations requiring from 10 to 20 watts. On the other hand, the power yield per pound is the lowest of all the supplies described, suggesting that if fuel is to be transported by air or some other high-cost route, perhaps another type of power would be preferable. Thermoelectric generators have been used in extremely cold climates by utilizing the generated heat to keep the fuel from freezing and in maintaining the electronic components within the operating range.

A. Background

It is becoming increasingly apparent that a comprehensive attempt to understand the mechanics of earthquake generation and to predict the time and place they will occur must be based on massive collection of pertinent data over large areas and the real-time analysis of that data at a central facility. Our current studies of the San Andreas fault system in central California (truly a small part of the region of concern) have already turned up some formidable telemetry problems: lack of adequate commercial facilities in large areas that require dense instrumental coverage, long waits for installation and/or improvement of phone systems, expectation that commercial communications links will fail during large earthquakes when continuity of data gathering is essential, etc. When one considers extension of such networks outside well-developed populated areas, it appears that a flexible, easily accessible, large capacity, long-range data transmission system is required (perhaps one based on a synchronous satellite). At NCER we have pondered these questions at length, and it seems clear that networks like the one we are operating in California generate such a large flow of data that a continuous multi-channel data transmission system is needed.

We are now beginning to experiment with automatic processing of seismic data from the California net. It may be possible to reduce the data flow from such a regional network by four or five orders of magnitude by "local" automatic event detection and timing and, thus, correspondingly to reduce the load on a data link to the central collection and analysis facility. In terms of present networks and processing capabilities, however, it is difficult to see how the proposed ERTS data collection system can be used. If the experiment in automatic processing leads to a workable system, the picture would change of course. There are also slowly changing geophysical parameters--earth strains (including tilting of the surface magnetic field, etc.--that could be sampled at intervals and relayed to a central processing facility via an ERTS-type system. Our understanding of the relationship of such parameters to earthquakes is still too poor to justify a large "prediction" system based on them alone, however.

In short, we cannot yet identify a simple set of parameters that can be sampled once a day, for example, that will permit us to judge whether a damaging earthquake is about to occur in the vicinity of the data collection point. The heart of the data collection and analysis problem lies in the earthquake-generating process itself. The region from which energy is drained to produce a large earthquake measures tens or hundreds of kilometers in length. Within this region, smaller earthquakes are frequent; and whether a given earthquake-producing "tear" will be arrested (and produce a small earthquake) or extend to dimensions that will result in a truly catastrophic one depends on the physical properties and initial state of the "system" that comprises a very large region. It appears that a more detailed understanding of the structure, history, and ambient state of such a region is needed than we believe can be acquired by periodic sampling of a few poorly understood geophysical parameters. At this time, it appears that the time of occurence, magnitude, and precise location of all significant earthquakes in such a region is the indispensable core of the data that are required. And as indicated above, until massive automatic digestion of seismic data from regional networks, yielding extremely condensed results such as arrival times and amplitudes (or even times, hypocenters, and magnitudes), is possible, the volume of seismic data that must be transmitted is enormous.

The hazard to man posed by volcanic eruptions around the world, however, is comparable to that posed by earthquakes, and the scientific tools used to study volcanoes include all of these pertinent to the study of earthquakes. Indeed, large numbers of small earthquakes occurring in or beneath a volcanic structure, together with measurable tilting of the ground around the volcano have turned out to be among the most easily detected and most readily interpretable manifestations of volcanic activity, except for the eruptive outbreaks themselves.

The habit of most volcanoes, especially the most dangerous ones, to lie dormant for decades or even hundreds of years between eruptions makes them extremely difficult to study individually. It is virtually impossible to maintain an effective up-to-date surveillance system on such a volcano during the long period of its quiescence. And by the time it reawakens, such systems as may have been established after a previous eruption almost invariably have degenerated till they are useless, if not abandoned altogether. It appears that a program of modest observations at a very large number of active volcanoes, organized and conducted by a single dedicated organization, would have an excellent chance of developing effective methods for predicting dangerous eruptions. Volcanoes also seem to be more amenable to simple schemes for condensing pertinent observations into concise numerical form than major earthquake-producing faults. The volcano itself is the focal point of activity: one knows in advance where to look for the symptoms related to changes in the internal condition of the volcano. Thus, a few multi-level earthquake-event counters placed thoughtfully around the volcano and queried daily may be expected to provide a useful and interpretable summary of earthquake activity in or near the volcano. Several tiltmeters strategically located around the eruptive center, also queried once or several times a day, should provide the most important strain data relative to the final buildup to an eruption.

For such a program of volcano observation to succeed, it will be necessary to collect data automatically recorded at many volcanoes and to transmit it to the center carrying out the volcano studies program. The volume and sampling interval of the required data seem to be compatible with the ERTS system; and the worldwide scope of the ERTS data collection system suggests that the most dangerous and interesting volcanoes of the entire world could be brought under continuous surveillance by its use.

B. Equipment

A total of about 50 platforms should be established initially in seven regions. It may be advantageous to collect data for each region at a central collection point; however, this would not appreciably affect the total data collected. Each platform will consist of 4 tiltmeters and 2 seismic-event counters.

Tiltmeters--Tiltmeters will detect changes of tilt in the earth with a resolution of 0.1 microradian. The sensors will be emplanted downhole to minimize surface and temperature effects and to insure a stable installation. At the present time tiltmeter electronics are being supplied by Develco, Inc., Mountain View, California, and the sensors are being constructed at the NCER machine shop. The present meter is not believed to be suited for the ERTS-proposed system, and although several different types are now under development, a suitable meter is not to be expected earlier than in one to two years. The present system will operate for a period of one year without a change of batteries; this will be a minimum requirement for all the components of the proposed system.

Seismic-Event Counters--This equipment is available commercially (Geotech Division, Teledyne Industries, Garland, Texas), but its high power consumption makes it unsuitable for the ERTS system. It is relatively simple to develop a low-power unit with the required specifications. Each event counter will have 3 outputs corresponding to input level separations of from 30 to 40 db, providing means of determining numbers of large intermediate, and small earthquakes.

Interfacing Equipment--Equipment will have to be developed to collect and store data from each sensor of a platform awaiting the satellite command for transmission.

C. Data Rates

Twelve-bit words are preferred for both seismic and tilt data although 8-bit words could be tolerated. One reading per day is required for each seismic-event counter, and three readings per day are preferred for each tiltmeter. It is assumed the data could be collected and stored by the interfacing equipment for transmission to the satellite upon interrogation. Assuming one interrogation per day, the following bit rates would be required per day:

a. Seismic-event counters:	72 bits
b. Tiltmeters:	144 bits
	216 bits/day/platform

D. Platform locations

Although we see an eventual need for at least 50 platforms throughout the circum-Pacific belt to monitor volcanic activity, we feel that the start of the program should be limited to a few test areas. This would allow us to evaluate the entire data collecting system, to study data obtained under an operational mode, and to gain experience in all phases of a volcano-surveillance network from site location and installation through data analysis.

We recommend that the program be started with a total of 16 platforms in the following test areas: Hawaii, the Cascade Range of Oregon and Washington, and in Central America.

Hawaii--Data recorded continuously at the Hawaii Volcano Observatory will provide a check on accuracy and completeness of platform data. Personnel at HVO will evaluate field installation and make recommendations for modifications. HVO will be the central data collection point. Volcanoes to be instrumented are: Kilauea, Manuna Loa, Hualalai, Two additional platforms will be moved from place to place in the Hawaiian Islands.

1. Kilauea

   a. Location: Southwest part of Island of Hawaii

      Lat. N19° 25.5'

      Long. W. 155° 17.5

   b. Height: 1222 meters above sea level

   c. Type: Shield volcano

   d. History: The historic activity of Kilauea has been largely concentrated within its caldera. Explosive activity has played only a very minor part in the building of Kilauea. Approximately 3.4 billion cubic meters of lava has been extruded by this volcano during historic time.

2. Mauna Loa

   a. Location: Southwestern part of the island of Hawaii

      Lat. N19° 28.5'

      Long. W155° 36.5'

   b. Height: 4170 meters above sea level

   c. Type: Shield volcano

d. History: Eruptions of Mauna Loa consist almost exclusively of the relatively quiet extrusion of fluid basaltic magma. From its first historic eruption, in 1832, to the present, Mauna Loa has averaged one eruption every 3.6 years and has been active approximately 6 percent of the time.

3. Hualalai

a. Location: Western part of island of Hawaii

Lat. N19° 41.5'
Long. W155° 52'

b. Height: 2515 meters above sea level

c. Type: Shield volcano

d. History: The only eruption of Hualaiai during historic times took place around 1800, when several flows were extruded. Several villages were buried, but there is no record of any casualties.

Continental United States--The volcanoes in the Cascade Range have been inactive for 80 to 100 years, but are important because of their proximity to populated areas. The volcanoes are in a seismically active region. Data from five platforms will be telemetered to one central collection point. The volcanoes to be instrumented are: Mount Baker, Mt. St. Helens, Mt. Adams, Mt. Hood, and Mt. Rainier.

1. Mount Rainier

a. Location: Approximately 100 km southeast of Seattle, Washington, in Mount Rainier National Park.

Lat. N46° 52'
Long. W121° 45.5'

b. Height: 4395 meters above sea level

c. Type: Strato-volcano

d. History: Records exist of six eruptions between 1843 and 1882. Steam is still issuing from the rocks along the smallest, and best defined, crater rim at the summit in sufficient volume to keep the rim free of snow and ice.

2. Mt. St. Helens

a. Location: On the western slope of the Cascade Range in Washington, 65 km north of the Columbia River. About 85 km NNE of Portland, Oregon.

Lat. N46° 12'
Long. W122° 11'

b. Height: 2975 meters above sea level

c. Type: Strato-volcano with small domes

d. History: The younger lave flows from Mt. St. Helens is estimated to be around 100 years old. Between 1842 and 1854 five eruptions have been recorded. Steam jets were reported in 1941.

3. Mt. Adams

a. Location: In the Cascade Range of Washington. About 115 km NE of Portland, Oregon.

Lat. N46° 12.30'
Long. W121° 29.50'

b. Height: 3751 meters above sea level

c. Type: Strato-volcano

d. History: Inactive during recent times

4. Mt. Hood

a. Location: In the Cascade Range of Oregon. About 75 km east of Portland, Oregon.

Lat. N46° 22.40'
Long. W121° 41.70'

b. Height: 3427 meters above sea level

c. Type: Strato-volcano

d. History: Inactive during recent times

5. Mt. Baker

a. Location: 25 km south of the Canadian border, Washington.

Lat. N48° 47.1'
Long. W121° 49.0'

b. Height: 3316 meters above sea level

c. Type: Strato-volcano

d. History: Five eruptions occurred between 1843 and 1870. Inactive at present.

Central America--Four volcanoes in Guatemala and two in El Salvador have been chosen to test an active area outside the United States where volcanoes are extremely hazardous to life and property. A detailed study will determine the number of data collection points, but two or three may be required. The volcanoes to be instrumented are: Santa Maria, Acatenango, Fuego, and Pacaya.

1. Santa Maria Volcano

a. Location: Southwest Guatemala, Departmento Quezaltenango.

Lat. N14° 45.5'
Long. W91° 32.9'

b. Height: 3768 meters above sea level

c. Type: Strato-volcano with explosion crater on SW slope and lava dome

d. History: Activity first noted in 1902 when a vast explosion removed 5.5 cubic kilometers of rock. Occasional eruptions have continued on through recent times. Greatest activity occurred between 1928 and 1932 causing loss of life and property. In November 1929 at least 23 people were killed.

2. Acatenango Volcano

a. Location: 40 km WSW of Guatemala City.

Lat. N14° 30.2'
Long. W90° 52.4'

b. Height: 3960 meters above sea level

c. Type: Strato twin volcano

d. History: Recent activity (after 1924) has been limited to eruptions of ash and bombs. This volcano is included because of its proximity (1 km) to Fuego.

3. Fuego Volcano

   a. Location: About 45 km WSW of Guatemala City.

      Lat. N14° 28.9'
      Long. W90° 52.9'

   b. Height: 3835 meters above sea level

   c. Type: Compound strato volcano

   d. History: Fuego is the most active volcano in Guatemala. Eruptions, landslides, and earthquakes attributed to activity in Fuego have resulted in property losses since 1582. In 1932 ashes fell as far as Salvador and Honduras and 140 kg meter of ash fell in one hour in Guatemala City.

4. Pacaya Volcano

   a. Location: About 30 km SSW of Guatemala City

      Lat. N14° 23.0'
      Long. W90° 36.2'

   b. Height: 2544 meters above sea level

   c. Type: Complex, strongly faulted volcanic mountain with two young cones at its SW peak, and a cluster of domes at its NW foot.

   d. History: Eruptions, often accompanied by earthquakes and subterranean rumblings, have been recorded. In October 1965, covered near by towns with rocks and ashes. Flaming lava was visible in Guatemala City. In 1961 Pacaya erupted for three days forcing the evacuation of 1,000 residents from the area.

5. Santa Ana Volcano

   a. Location: Western Salvador

      Lat. N13° 51.2'
      Long. W89° 37.8'

   b. Height: 2181 meters above sea level

   c. Type: Strato volcano

   d. History: Weakly active through 1955. Primary interest in this volcano is its proximity to Izalco.

6. Izalco Volcano

a. Location: Western Salvador, on the southern slope of Santa Ana Volcano.

Lat. N13° 48.9'
Long. W89° 38.1'

b. Height: 1965 meters above sea level (January 1956)

c. Type: Strato volcano

d. History: This volcano has been active continually since the late 1700's with outflow of lavas interrupted by strong explosions, which were generally accompanied by subterranean rumbling. Life and property have been lost during an eruption of this volcano.

The above platform locations are tentative, and after coordinating the work with other local university and government organizations, we may wish to make minor modifications. It is understandable that there are other equally important areas such as the Aleutians, Philippines, etc., but these regions have special environmental, logistics maintenance, and other problems that can be solved after the volcano-surveillance network is operating satisfactorily.

Each platform will consist of 4 tiltmeters and 2 seismic-event counters. A total of 216 bits/day/platform will be required.

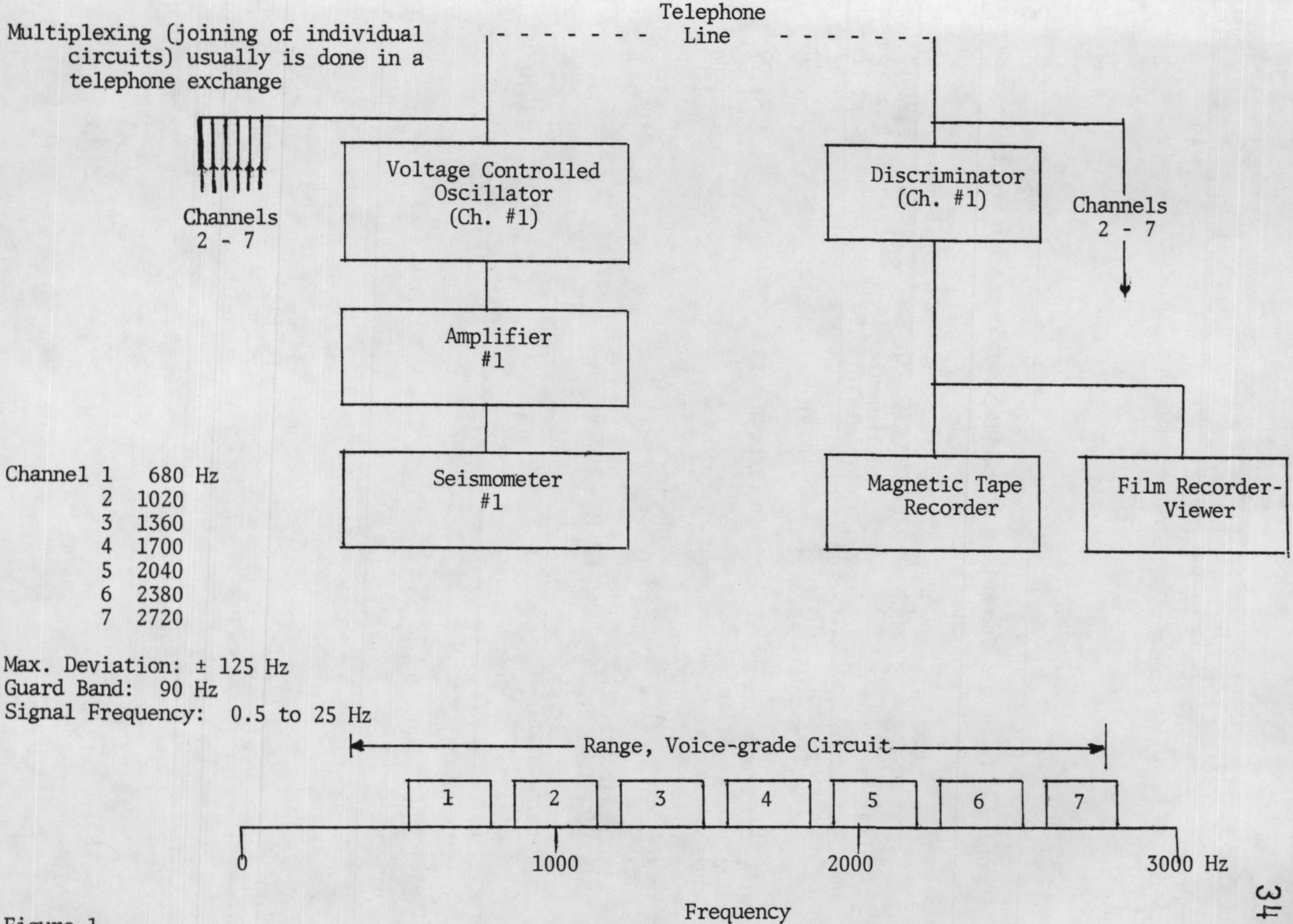
Telephone
Line
Multiplexing (joining of individual circuits) usually is done in a telephone exchange
Channels 2 - 7
Voltage Controlled Oscillator (Ch. #1)
Amplifier #1
Seismometer #1
Discriminator (Ch. #1)
Channels 2 - 7
Magnetic Tape Recorder
Film Recorder-Viewer
Channel 1 680 Hz
2 1020
3 1360
4 1700
5 2040
6 2380
7 2720
Max. Deviation: ± 125 Hz
Guard Band: 90 Hz
Signal Frequency: 0.5 to 25 Hz
Range, Voice-grade Circuit
1
2
3
4
5
6
7
0
1000
2000
3000 Hz
Frequency

Figure 1.

Table 1. Power requirements for various components of a remote seismograph station.

Unit	Power Requirement (watts)	Yearly Power Requirement (watt-hours)
1. VCO-Preamplifier	0.30	2,600
2. Transmitter	0.48	4,200
3. Receiver	0.66	5,800
Remote Station (1 and 2)	0.78	6,800
Relay Station (1, 2 and 3)	1.44	12,600

Table 2. Power Sources.

Type of Power Source	Power Rating	Voltage	Life	Weight (Pounds)	Watt-Hours per pound	Watt-Hours per dollar
Lead-acid battery (Sears)	80 AH	12	6 mos	48	20	64
Air Cell (Union Carbide Model 2S10)	1000 AH	2.5	3 yrs	32	78	122
Solar Cell (Central Lab Model CSP14D) charging a Nickel Cadmium battery	6 watt-hrs per day (av)	12	?	12	?	15 /1
Thermoelectric Generator (3M, Model 515)	20 watts	12	?		15 /2	260 /2
Isotope Generator (U.S. Underseas Cable Corp., Model ITG-101/5)	1 watt	12	5 yrs	350	125	5

/1 Assuming life of 3 years.

/2 Rating based on cost and weight of propane fuel only.